

DESIGN AND PERFORMANCE OF A COMPACT PASSIVE HYDROGEN MASER

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ABSTRACT

The development of a compact passive hydrogen maser has been completed by Ball Aerospace Systems Division. We describe the design and operation of a number of subsystems in the unit. These include a self-starting low power r.f. dissociator, a combination getter/ion pump vacuum system, a small hydride source of molecular hydrogen, and a method of automatically locking to the microwave resonance. We also report the measurement of performance of the maser as a whole.

INTRODUCTION

This report summarizes some engineering and development made on a compact passive hydrogen maser (CPHM-100). The maser is based on a design begun at the National Bureau of Standards in Boulder, Colorado⁽¹⁾. The intent of this work has been to make a commercial device with approximately a ten-year lifetime, fully automated, which is fairly rugged and operable over the commercial temperature range, while preserving the small size and the frequency performance of the NBS laboratory standard. In particular, $\sigma_y(\tau) < 2 \times 10^{-12} \tau^{-1/2}$, with longer term stability of better than one part in 10^{14} . A more complete list of maser specifications is given in Table 1.

A number of technical improvements were necessary in order to achieve these goals. They include development of a hydride source of molecular hydrogen, a getter/ion pump vacuum system, a new r.f. dissociator design, thermal design improvements, and an automatic lock to the microwave resonance on start-up.

GENERAL DESCRIPTION

The CPHM-100 passive hydrogen maser (Figure 1) uses an alumina ceramic chamber, which is silver-plated on the outside to form a dielectrically loaded TE011 microwave cavity, and coated with tetrafluorethylene-hexafluoropropylene copolymer (DuPont Teflon FEP120) on the inside to form a containment vessel for the hydrogen atoms. The maser cavity is surrounded by four layers of magnetic shielding, one layer of thermal control, and two layers of thermal insulation.

Upper state hydrogen atoms are transmitted to the cavity by dissociating molecular hydrogen in a glass bulb, forming a beam of atoms by means of a single-hole collimator, and passing the atomic beam through a quadrupole state selector magnet. Atoms which subsequently leave the cavity, as well as those which are state-rejected by the magnet, are removed by the maser vacuum pump.

The electronic system for the passive maser is shown in Figure 2. In this system, two phase modulations are imposed on the microwave carrier which passes through the maser cavity. One modulation at 12 Hz gives information about the hydrogen resonance, and the other modulation at 12 kHz is used to lock the center of the microwave cavity resonance to the center of the hydrogen resonance. In this manner, the effect of cavity frequency pulling is reduced. In both cases the separate servo loops must maintain lock relative to line center to one part in 10^5 in order to achieve the stated frequency stability specification of 1×10^{-14} .

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HYDRIDE SOURCE

A bottle of hydrogen gas sufficient to supply this maser for the proposed ten-year lifetime would be unreasonably large and hazardous in transport. Consequently, we have elected to use a LaNi_5 hydride source.^(2,3) The source contains about 180 grams of the hydride (Ergenics Hy-Stor 205) which is sufficient to provide 0.4 mole of hydrogen to the maser. Flow rate of the hydrogen is regulated by adjusting both the temperature of the hydride source and the temperature of the palladium-silver alloy variable leak which follows it. The entire source, including the variable leak, thermal insulation, and temperature controller, occupies about 1000 cubic centimeters, and requires less than 8 watts of power for continuous operation at 0 °C. At the estimated consumption rate of .03 mole/year, the hydride source should supply enough hydrogen for 13 years. Additionally, the hydride source is exceptionally pure, especially when combined with the palladium leak, avoiding contamination of either the dissociator bulb or the maser cavity.

VACUUM SYSTEM

Hydrogen is removed from the maser by a nonevaporable solid getter pump.^(3,4) We use a mixture of zirconium and zirconium-vanadium-iron alloy (SAES St172). The 600 grams of getter material is sufficient to pump the .4 mole of hydrogen used by the maser over its lifetime. Pump lifetime predictions are based on both data from SAES Getters, Inc., and on accelerated lifetime measurements in Ball Laboratories. In the Ball measurements, small quantities of getter material were exposed to a controlled flow of hydrogen until signs of getter deterioration were observed. Unlike other getter materials, the Zr-V-Fe getter may be activated at temperatures as low as 450 °C, which allows activation in situ without damage to other maser components. Thermal shields and low conductivity materials are used in supporting and housing the getter elements, so that activation is achieved with input power levels as low as 50 watts.

The getters also remove small amounts of gases such as oxygen, nitrogen, and water vapor, but little or no helium or argon. For this reason, two 2 l/s ion pumps are used in addition to the getter pumps in order to remove such gases. The getter pump is placed between the ion pumps and the rest of the maser, so that very little hydrogen reaches the ion pumps. Consequently, the ion pump current is less than 8 microamperes, leading us to predict pump lifetimes well in excess of ten years.

The getter pump system offers other advantages as well. The power supply may be turned off for long periods of time, and the ion pumps will still restart, since the getter pump has been maintaining a reasonably low pressure. Power outages in excess of four weeks are possible. This allows the maser to be shipped to a destination and to be stored for several days before turning the unit on, and yet no special procedure is required for start-up.

All portions of the vacuum system have been made modular with metal vacuum seals, so that the getter unit can be assembled and replaced separately from the hydrogen source, the ion pumps, and the hydrogen dissociator. The complete assembly is rugged, permitting the maser to be shipped by air freight and truck without special precautions.

HYDROGEN DISSOCIATOR

The hydrogen dissociator was also redesigned in order to improve lifetime, reliability, and to make it modular. Previously, epoxy vacuum joints and seals were used in the dissociator. These seals were all replaced with metal and glass construction, in order to avoid long-term degradation of the epoxy. The dissociator bulb is made of pyrex, 1.9 cm in diameter and 5 cm long, with a pyrex collimator tube at one end of the bulb. The exit hole in the collimator is 0.1 mm in diameter and 2.5 mm long. The bulb is attached by means of a glass-metal

transition to the stainless steel vacuum flange. Hydrogen gas flows into the bulb through a VCR vacuum fitting welded to the side of the main vacuum flange. The quadrupole state selection magnet is attached to this flange also, with alignment of the atomic beam determined by mechanical tolerances during fabrication. The entire dissociator assembly is attached to the maser by one 4.5 inch Conflat-type flange, and one 1/8 inch VCR fitting.

Previous designs of the radio frequency discharge method were unreliable, sometimes failing to start the r.f. plasma discharge, or requiring high power levels. As a remedy to this problem, we have adopted a means of coupling the r.f. to the hydrogen which initially creates high electric fields to instigate the discharge, and then magnetically couples energy into the plasma. In this manner, the discharge is self-starting, and yet requires very little r.f. power. While the discharge will start and run on as little as .25 watt of r.f. at 200 MHz, better dissociation efficiency is obtained at 2 to 3 watts. Nominal hydrogen pressure in the discharge bulb is 100 microns, but pressures of 20 to 200 microns have been used.

THERMAL DESIGN

The basic thermal control of the maser has three mutually interacting circuits. The first is a thermistor bridge temperature sensor and transistor heater element which are mounted to the aluminum oven cylinder shown in Figure 1. This circuit brings the maser cavity to approximately 70 °C. A second control loop detects the 12 kHz AM on the microwave signal which passes through the cavity (Figure 2). This AM signal is a measure of the detuning of the microwave cavity center from the hydrogen resonance line, and is used to tune a varactor circuit on the input to the cavity, keeping the cavity tuned to a fixed frequency. This loop is relatively fast, with a response time of about ten seconds, but a limited tuning range of about 10 kHz at the 1.42 GHz resonance frequency. This tuning range corresponds to a cavity temperature change of about 0.15 °C. A third loop detects the error signal voltage of the second loop, and adjusts the set point of the thermistor control to null the error. This gives a very wide dynamic range on the temperature control, with a slow response time. Shortcomings in the implementation of this design prompted certain improvements in the thermal design which resulted in faster warm-up, lower power consumption, higher temperature stability, and tolerance of greater changes in ambient temperature.

The first improvement combined an increase of thermal conductivity from the thermistor control to the ceramic cavity with a reduction of the thermal conductivity from the oven layer to the outside of the maser. The former change required changing the method of shock mounting the cavity, so that thermally insulating components were eliminated, and increasing the cross section of some internal structures in order to increase thermal conductivity. The latter change was made by using insulation with a lower coefficient of conductivity (Min-K by Johns-Manville). These changes resulted in a warm-up time of four hours from ambient temperature of 25 °C, and a continuous power consumption of less than 20 watts. In addition, the thermistor bridge now controls the temperature to within the tuning range of the varactor circuit for modest changes in room temperature, even when the third control loop is disabled.

A second improvement is provision for feedforward compensation. Thermistor sensors placed on the outer magnetic shield of the package give a small correction to the thermistor bridge set point which is proportional to the change in thermal loss through the insulation. This technique anticipates temperature shifts with room temperature changes which are due to thermal gradients across the oven cylinder. The result is a faster control of large external temperature changes.

AUTOMATIC LOCK

Field operation of a hydrogen maser requires an automatic start-up sequence, lock acquisition, and fault indication. The discriminator curve formed by the demodulated microwave signal as the carrier frequency is swept across the hydrogen resonance is quite simple (Figure 3). However, the 12 Hz sidebands of the modulated carrier produce a fairly complicated structure to each side of the central hydrogen resonance (Figure 4). It is possible that aging of the 4.9 MHz quartz oscillator will cause the maser to lock to the wrong feature in this spectrum at start-up. In order to prevent this from occurring, the 12 Hz modulation is switched off initially, and the 12 kHz phase modulated carrier is swept across the hydrogen resonance (5). This produces the single feature shown in Figure 5. When this feature is detected, the sweep is halted, and the 12 Hz modulation turned on. Since the nearest sideband features are separated by 12 kHz from the carrier during the sweep, aging of the quartz oscillator will not cause a false lock.

The philosophy of fault indication and automatic restart is based on positive indicators. That is, certain monitor values must be met in order that a lock condition exists. For example, one circuit continuously monitors the 24 Hz AM on the carrier (a measure of atomic hydrogen flux), another one senses the molecular hydrogen pressure, and another collection of circuits monitors the several internal loops of the offset frequency synthesizer (Figure 2). If any of these monitor voltages move outside of acceptable limits, a fault indication is set, and the automatic lock switches to some prior step in the locking sequence, depending upon the specific fault.

Finally, the start-up sequence from a cold start proceeds as quickly as possible with minimum power consumption. For example, the oven heaters are turned full on at first, while most of the other electronic circuits are left off. At a predetermined set point in the cavity temperature, other systems are activated, and the heater power consumption reduced. This process continues until complete lock is achieved. Frequency lock is usually achieved in 3 hours starting from room temperature.

CONCLUSIONS

A number of improvements have been made in a compact passive hydrogen maser, CPHM-100. These include development of a hydride source of molecular hydrogen, a combination getter/ion pump vacuum system, a low power self-starting r.f. dissociator, improved thermal design, and automatic sequencing for start-up and line lock.

The completed unit is shown in Figure 6. Performance specifications are given in Table 1. Typical microwave spectra, both experimental data and theoretical fits, are given in Figures 3, 4 and 5. Figure 7 shows the frequency stability of the Ball compact passive hydrogen maser versus an NBS hydrogen maser. This data was taken with an engineering model of the maser (EM 1), which did not have all of the improvements described in this article. However, the data shown in Figure 7 is representative of the frequency stability of the final maser design.

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Table 1. CPHM-100 Specifications

Electrical:

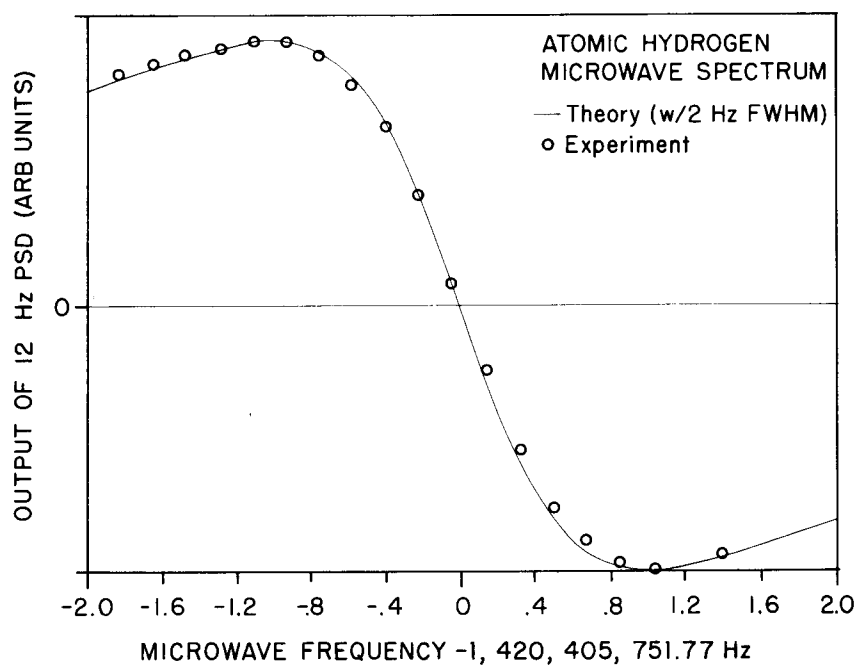
Output	5-Mhz sinewave, 1 V rms into 50 Ω 2 buffered outputs, > 100 dB isolation
Phase noise, $\mathcal{L}(f)$	< -113 dB at 1 Hz < -135 dB at 10 Hz < -155 dB at ≥ 100 Hz
Short term stability, $\sigma_y(\tau)$	< 2×10^{-13} at 100 s < 2×10^{-14} at 10^4 s < 1×10^{-14} at 1 day
Frequency drift	< 1×10^{-15} / day
Maximum frequency change	< 1×10^{-12} for the life of the unit
Retrace (turn off / turn on)	< 5×10^{-13}
Input power	< 150 W at 28 Vdc
Warm up time	< 4 hours at 25C ambient
Tuning resolution	1×10^{-14}

Environmental:

Temperature coefficient	< 5×10^{-14} / C
Magnetic field sensitivity	< 1×10^{-14} / 0.1 Oe

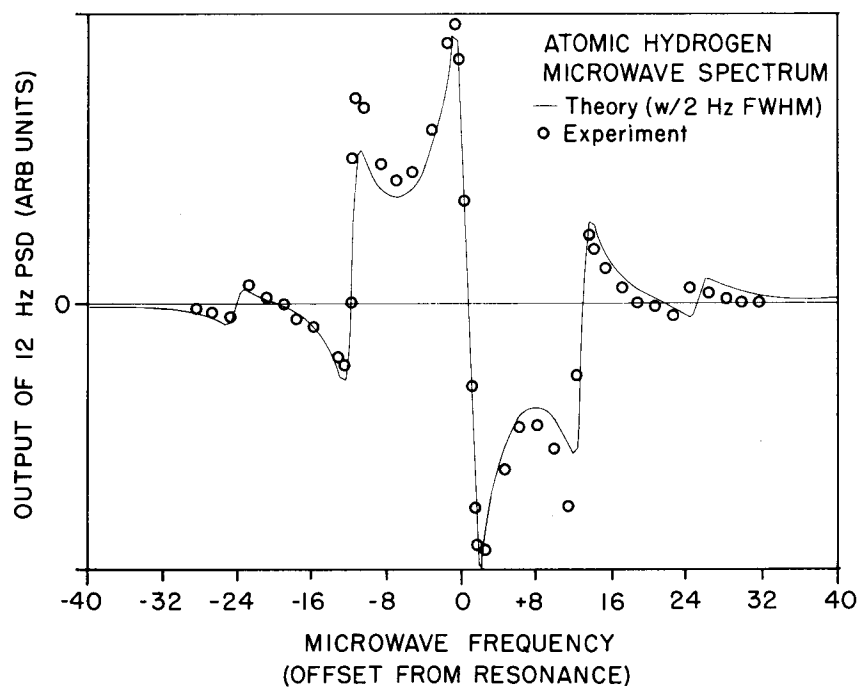
Physical:

Size (rack mounted chassis)	10.5 in. high \times 23 in. deep \times 19 in. wide
Weight	150 lbs.



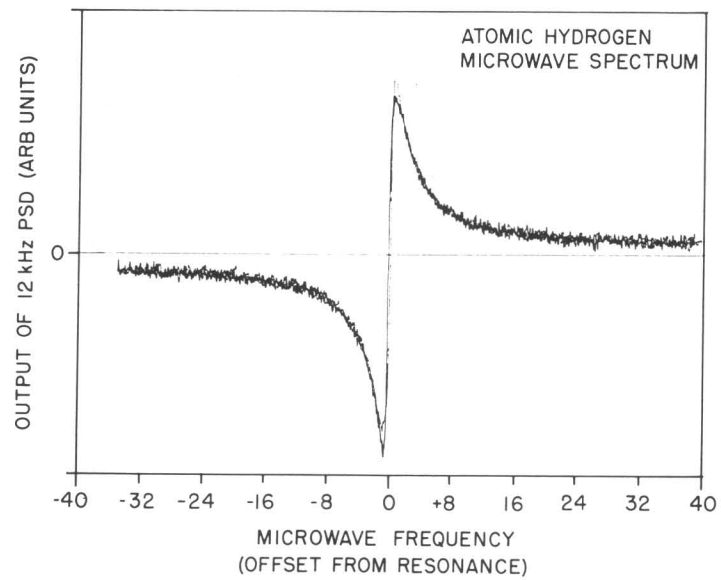
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Figure 3. Atomic Hydrogen Microwave Spectrum



A/N 8476₇

Figure 4. Atomic Hydrogen Microwave Spectrum



- EXPERIMENTAL WITH 12 KHz MODULATION ONLY
- THEORETICAL WITH 2 Hz LINEWIDTH

A/N 8476is

Figure 5. Autolock Atomic Discriminator

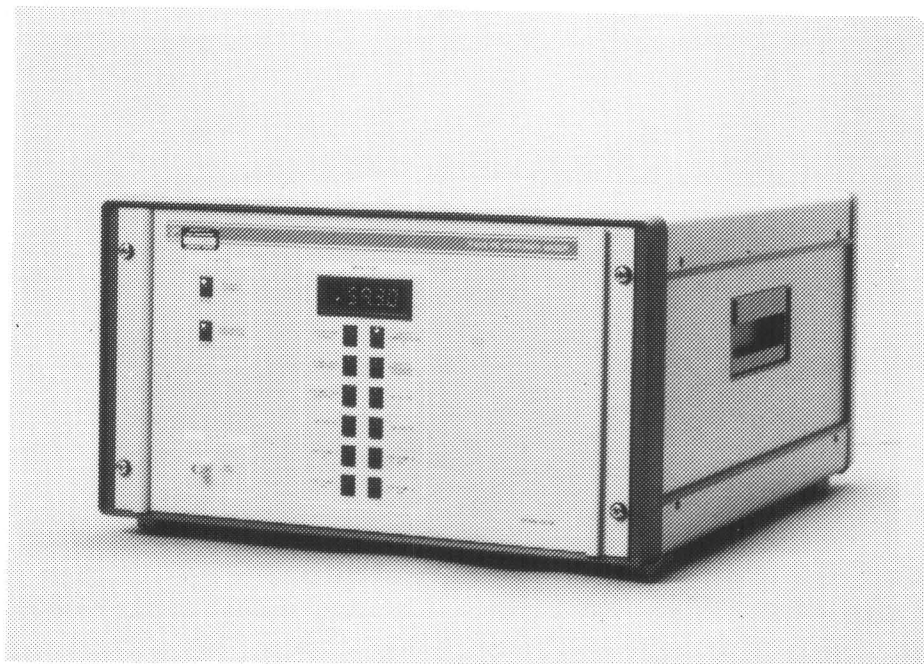


Figure 6. Model CPHM-100

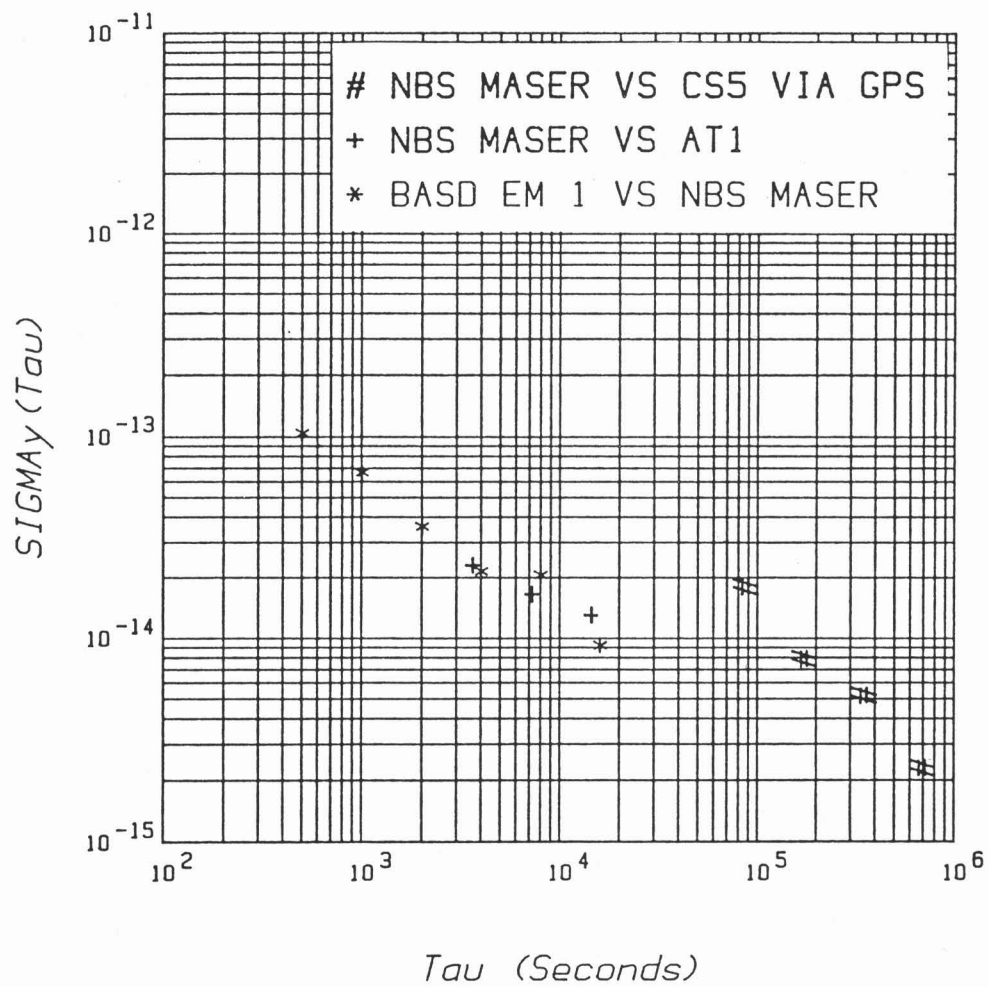


Figure 7. CPHM Frequency Stability